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Original article

CRUST: Software for the implementation of Regional Chronology Standardisation: Part 1. Signal-Free RCS

Thomas M. Melvin*, Keith R. Briffa

Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

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ABSTRACT

This is the first of a two-part description of a new software tool CRUST (**C**limatic **R**esearch **U**nit **S**tandardisation of **T**ree-ring data). This program has been designed primarily to allow the convenient, routine application of "Signal-Free Regional Chronology Standardisation" (SF RCS) to different types of tree-ring data. The program also enables the use of other popular standardisation methods. A series of experiments is described in which the ability of simple RCS and SF RCS to recover known tree-growth forcing signals is tested. In the comparatively rare situation where many sub-fossil data are distributed over a wide time range and there is no slope in the overall common-growth forcing signal, simple RCS is satisfactory. Simple RCS produces distortion in all other examples explored here. SF RCS is superior to simple RCS and in all cases examined. SF RCS works well except when the span of starting dates of sample trees is too narrow, a situation for which a test is available. Based on the results of the tests explored here, we conclude that Signal-Free RCS should be used as the standard method of RCS processing.

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Introduction

In dendroclimatology the changes seen in series of annual tree-ring measurements are used to identify changes in the common forcing of tree growth over time and in some circumstances this changing growth rate of trees is used as a "proxy" for changing climate. Tree-ring measurements also contain variations that are unrelated to climate: caused by biological and mechanical constraints on tree growth encountered as the tree becomes older and larger. These changes are referred to as the "age-related-growth trend" or the "expected growth curve" i.e. the changes in a series of tree-ring measurements throughout the life of a tree growing in an unchanging climate. These changes need to be removed from the measurements in order to better isolate growth variations caused by climate variability (Fritts, 1976, Chapter 6, Cook et al., 1990). The process of removing the age-related growth trend (detrending) to produce indices of tree growth is called "standardisation". Traditional methods of detrending involved fitting a curve to the measurement series and removing the variance represented by the fitted curve. Depending on the longevity of trees, this process removes substantial, and in many cases all, long-timescale variance from a chronology and imposes serious low-frequency limitations in subsequent dendroclimatic reconstructions (Cook et al., 1995; Briffa et al., 1996). In order to overcome this frequency limitation it is necessary to estimate and remove the expected non-climate growth rate change in tree-ring measurements independently of the growth of individual trees.

Regional Curve Standardisation (RCS) was introduced to dendroclimatology (Briffa et al., 1992) to overcome the frequency limitation of curve-fitting standardisation. It does so by using the average of the measurements of the rings of all trees at each ring age as the expected growth value for each individual tree. RCS has been used in various forms for nearly a century (Huntington, 1914; Erlandsson, 1936; Briffa et al., 1992; Esper et al., 2002). A review of the background and implementation of RCS is provided in Briffa and Melvin (2011). There are a number of problems associated with RCS and these may to some extent have prevented the widespread uptake of this method. In RCS, as normally implemented to date, it is assumed that any influence of the common signal on the shape of the RCS curve will be removed by the process of realigning measurement series by ring age and averaging. In effect, large numbers of sub-fossil (or historical or archaeologically sourced) trees which grew over widely differing periods are needed for this averaging process to be effective (Briffa et al., 1992, 1996). This requirement severely restricts the application of RCS to sites with substantial amounts of sub-fossil samples. Melvin and Briffa (2008) introduced the concept of "signal-free" standardisation where the detrending curve is estimated using measurement data from which the common growth-forcing signal has been removed i.e. where the detrending curve is not distorted by the effect of climate forcing. This method was originally described in the context of curve-fitting standardisation. However, the signal-free method can also be used

* Corresponding author. Tel.: +44 01603 593161; fax: +44 01603 507784.
E-mail address: t.m.melvin@uea.ac.uk (T.M. Melvin).

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to create an RCS curve that is not biased by the common signal and this largely reduces the need for many sub-fossil data. The benefits and limitations of the application of the signal-free method in RCS, particularly for standardising “living tree” data are evaluated and discussed here. Another factor that has, up until now, limited the uptake of RCS is the lack of widely available software. Here we introduce CRUST (**C**limatic **R**esearch **U**nit **S**tandardisation of **T**ree-ring data): a software package that can be used for routine implementation of, and experimentation with, SF RCS and other types of tree-ring standardisation.

In the two companion papers, of which this is Part 1, we describe a number of RCS implementation options. Herein, we focus on the use of signal-free RCS (SF RCS) and describe the basic functions of CRUST. In Part 2, we focus on other aspects of the use of CRUST, making specific implementation recommendations and suggesting the use of various diagnostic procedures when using SF RCS. We begin here by providing some background to the concepts of simple and SF RCS. We then describe the implementation of RCS in CRUST and describe a number of examples selected to demonstrate how it performs in practice.

Background

Preservation of long-timescale variance

We define three frequency ranges, relative to the lengths of tree-ring series; firstly, low-frequency chronology variance is considered to be at timescales beyond the age of a tree; secondly, medium-frequency variance spans time scales from decades to the age of a tree; and thirdly, high-frequency variance is that at sub-decadal timescales. When using curve-fitting standardisation methods the mean of each series of tree indices is set to 1.0. The mean of the chronology indices over the length of a tree will be close to 1.0 and there will be no low-frequency variance in resulting chronologies (Cook et al., 1995). When a sloping line is fitted to series of measurements the slope, over the life of the tree, is removed from the resulting tree indices, further limiting the retention of medium-frequency variance. In RCS, the value of each tree index is set relative to the value of the RCS curve at that ring age and the average value of each index series can, therefore, vary considerably. The low-frequency variance of an RCS chronology is based on the changing value of the mean growth rate of trees over time. In RCS, the slope of each series of tree indices is set relative to the slope of the RCS curve and the resulting index series for a tree can slope up or down enabling RCS to preserve medium-frequency variance.

Simple RCS method

It is possible to implement RCS in different ways and various approaches or refinements have been explored to date (see discussion in Briffa and Melvin, 2011). We use some commonly used procedures to define “simple RCS” which forms the basis for the comparisons with alternative implementations of RCS discussed here. In simple RCS all series of ring measurements for a site are aligned by cambial age and the arithmetic average of measurements is used to produce a curve of mean measurement by cambial age. When available, “pith-offset” estimates are used in the assessment of ring age, otherwise the first ring is presumed to be the first year of tree growth. The “mean measurement by ring age” curve tends to be noisy and needs to be smoothed. Here we use a time-varying response spline (Melvin et al., 2007), to create a smoothly varying RCS curve. This RCS curve is taken to represent the expected measurement value for each year of growth in an unvarying climate. Each ring-width measurement is then divided by the RCS curve value for its particular ring age to give a dimensionless tree index. These indices are fractional deviations. The arithmetic mean of all tree indices for a particular calendar year is the chronology value for that year.

A conceptual RCS model

Melvin (2004, p. 53–56) describes a simple multiplicative model of tree growth and adapts this model for use with the signal-free method in the context of curve-fitting standardisation (Melvin and Briffa, 2008). This can be described by a series of conceptual equations:

Ring width = Expected growth * Chronology index * Error
Tree index = Ring measurement/Expected growth
Tree index = Chronology index * Error
SF measurement = Ring measurement/Chronology index
SF measurement = Expected growth * Error.

When using curve-fitting standardisation methods, the mean error over the life of a tree will be close to one and this error can be treated as random noise.

For practical purposes a ring growth model need only define those factors that can be effectively isolated in analysis, with the influence of un-resolvable factors considered as part of the chronology error. In RCS, “Expected Growth” is the RCS curve value for the appropriate ring age and low-frequency variance is preserved in the mean value of each series of tree indices. If, for convenience, we ignore any uncertainty in the RCS curve itself we can consider the RCS chronology error as composed of separate parts. Firstly, there is the medium- plus high-frequency error (equivalent to that resulting from the use of curve-fitting methods). This arises from differences in series of tree indices which have been rescaled to have mean values that are equal to the mean of the chronology over their common period and represented as fractional deviations from chronology values. Secondly, there is the low-frequency error, unique to RCS, which is the error (as fractional deviations) in a chronology created by averaging series of mean values for each tree i.e. where for each tree all index values are replaced by the mean index value. The medium- to high-frequency error is independent of that for low frequencies. In this discussion we are principally concerned with aspects of the low-frequency chronology and its uncertainty.

For the RCS growth model we can write:

Ring width = RCS curve value * Chronology index * Mean offset * Error
Tree index = Ring measurement/Expected growth
Tree index = Chronology index * Mean offset * Error.

These equations suggest the use of several techniques for diagnosing problems and for reducing bias in the use of RCS. “Mean Offset” is a factor by which a series of indices from one tree must be divided in order to adjust its mean to be the same as the mean of the chronology over their common period. In a signal and noise context, the average of mean offsets for all tree-index series provides a measure of the chronology error representing within-site variations in overall tree growth rates. This also provides a benchmark for investigating the degree of homogeneity in low-frequency growth rates within sites, or across groups of sites in a wider-regional chronology, and for comparing different growth rates as represented in separate sample sources (e.g. sub-fossil, archaeological or living tree samples). The “noise” represented by mean offset needs to be taken into account in the assessment of low-frequency chronology signal strength. This is discussed in the companion (Part 2) to this paper.

For the RCS growth model we can define signal-free measurements:

SF measurement = Ring measurement/Chronology index.
SF measurement = RCS curve value * Mean offset * Error.

Dividing a ring measurement by the chronology index gives an estimate of growth that might have occurred in an average climate year (a signal-free measurement). Dividing ring measurements by the appropriate RCS curve value and multiplying by the value at another ring age provides an estimate of the expected growth rate at that alternative ring age and enables conversion of all rings to those "expected" for any specific ring age. This is useful in the exploration of the efficiency of using "multiple" rather than "single" RCS curves and is also discussed in Part 2.

Using the Signal-Free method with RCS

An example of how an RCS curve can be distorted by the presence of common signal would be where the "old" section of the RCS curve was made up of average ring widths only from old trees that germinated at a similar date. The RCS curve would contain variance representing the common climate signal in ring widths from these trees in addition to the non-climatic, "biological" decline in ring width. However, because the pattern and magnitude of chronology common signal is known (or at least can be reasonably estimated as the chronology variance), this signal can be removed from all measurement series by division, creating series of SF measurements. An RCS curve created from SF measurements (SF RCS curve) will display minimal influence from the long-timescale variance of the common forcing signal. The signal-free method thus has the potential to remove, or reduce, the need for large numbers of sub-fossil trees when constructing an RCS chronology. The CRUST program provides a convenient way of implementing this approach. Here we describe the SF RCS and show how the existence of medium-frequency variance in the common forcing of tree growth can distort the shape of the simple RCS curve leading to systematic bias in the (non-signal-free) RCS chronology when this is constructed with insufficient sub-fossil samples. We also demonstrate how the use of the signal-free method can mitigate this problem.

Implementing the Signal-Free method

Chronology indices, as the mean of tree indices which are fractional deviations, represent the magnitude of common forcing of tree growth in each year as a fraction of the average value of tree indices. Dividing each ring measurement by the appropriate-year chronology index will remove the variance representing the common forcing of tree growth from each series of measurements. Melvin and Briffa (2008), describe the application of the signal-free method in the context of "curve-fitting" standardisation. The process is applied iteratively. When applied in the case of RCS, a chronology is first produced using RCS standardisation. Each measurement value is then divided by the appropriate chronology value for that year to produce a set of SF measurements. If the common signal has been effectively removed from all measurement series, a chronology created by standardising these SF measurements will have virtually zero variance. This will not be achieved in the first iteration. The SF residual-chronology represents distortion arising from the effect of residual common signal on the RCS curve and is removed from the chronology by multiplication i.e. SF residual-chronology times chronology. Therefore, the standardisation is repeated but this time using the SF measurements, creating a new SF RCS curve and a SF residual-chronology. The process is repeated until the point where the SF residual-chronology has near-zero variance. In practice, the magnitude of the variance of the SF residual chronology is roughly 20% of its value from the previous iteration. A zero-variance SF residual-chronology is considered to be one where all values are within the range 1.0 ± 0.002. This is achieved generally within 4 or 5 iterations. At this point the "final" SF RCS curve is unaffected by the medium-frequency variance of the external growth-forcing signal and when used to standardise the original measurement series will yield an optimum SF RCS chronology.

In CRUST, an "RCS standardisation" procedure, which creates an RCS chronology, is called repeatedly as part of the process of developing a SF RCS chronology. We can therefore, summarise the RCS process as follows:

RCS Standardisation:

1. Average the measurement data into a mean curve by ring age.
2. Smooth the RCS curve.
3. Divide measurements by appropriate cambial age values of the smoothed RCS curve to create tree indices.
4. Average tree indices by calendar year to create the RCS chronology.

In CRUST, RCS standardisation allows a selection from the various available implementation options e.g. using multiple RCS curves, using diameter based RCS curves, using basal area increment, or using robust means etc. (see *Principal CRUST standardisation options*).

Signal-Free method:

1. Set the SF measurement values to the original measurement values.
2. Set all SF residual-chronology values to 1.0.
3. Set all chronology values to 1.0.
4. Divide SF measurements by the SF residual-chronology values.
5. Create a SF residual-chronology using SF measurements with "RCS Standardisation" as above.
6. Multiply the chronology by the SF residual-chronology.
7. Repeat 4 through 6 until all SF residual-chronology values are less than 0.002.

After the final iteration the accumulated chronology (from 6) is the final SF RCS chronology and a final set of signal-free tree indices is created by the division of the original measurements by the final SF RCS curve values for the appropriate ring ages.

Examples of Signal-free in practice

To illustrate and compare the effectiveness of different aspects of simple versus SF RCS processing in practice we use various data sets. Simulated tree-ring data sets were created with known common-growth forcing. Various existing data sets, comprising real measurement series, are also used. The ability of both simple and SF RCS to recover an artificial change without bias is assessed by applying artificial changes to existing TRW data, processing the resulting data sets, and then comparing the results. The *Torneträsk TRW* data "torn-all.raw" (Grudd et al., 2002, updated by Melvin et al., 2012), spanning the period from 500 BCE to 2010 CE from 467 sub-fossil and 163 living trees, are used to provide example sub-fossil and living-tree chronologies. Here, the *Yamal TRW* data "yml-all.raw" (Hantemirov and Shiyatov, 2002, updated by Briffa et al., 2013), spanning the period from 500 BCE to 2005 CE from 473

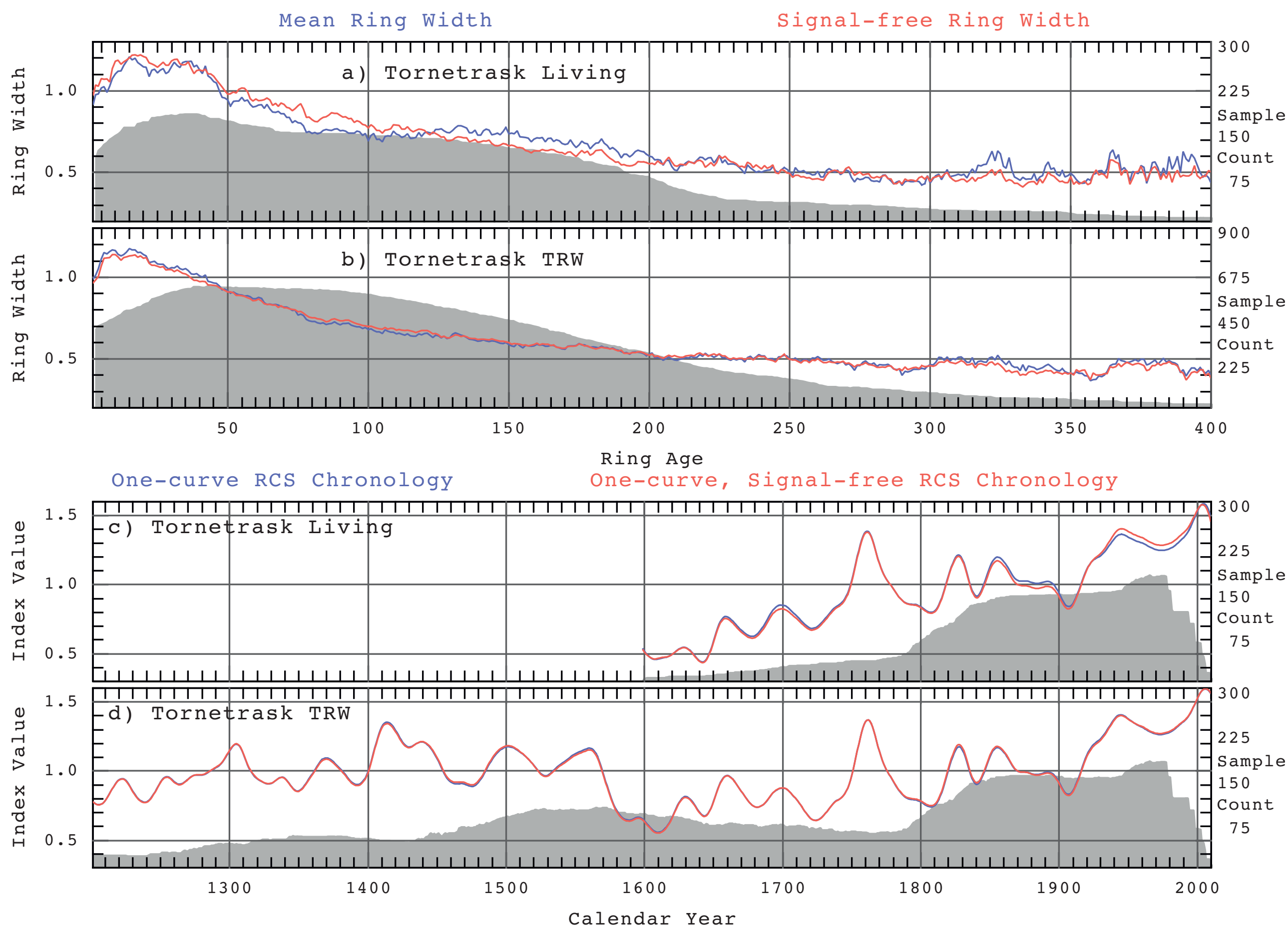

Fig. 1. A subset of living-tree data (*Torneträsk Living*) was extracted from the Common Era portion of the *Torneträsk TRW* data set comprising sub-fossil and living-tree measurements. The data sets were each standardised using one-curve RCS in two ways: first, without using the signal-free method (blue lines) and second, using the signal-free method (red lines). The unsmoothed RCS curves for the *Torneträsk Living* data are plotted in (a) and for all the *Torneträsk TRW* data in (b). The chronologies for *Torneträsk Living* are plotted in (c) and for *Torneträsk TRW* in (d). Chronologies have been smoothed here with a 50-year spline and sample counts are show by grey shading.

sub-fossil and 160 living trees, are used as the basis for developing example sub-fossil TRW data sets. The *Finnish TRW* data “Finn-mrg.raw” (Melvin, 2004) derived from 100 living-trees, spanning the period 1550–2000 CE, are also used as the basis for developing example living-tree data sets.

Living-tree and sub-fossil chronologies

The Common Era portion of the Torneträsk ring-width chronology (called *Torneträsk TRW*) is used as an example sub-fossil chronology. A separate “modern” chronology was created using data from only those trees with rings after 1960 (called *Torneträsk Living*). One-curve RCS was used to standardise both data sets, firstly without using the signal-free method (simple RCS) and secondly using the signal-free method. The resulting unsmoothed RCS curves and chronologies are compared in Fig. 1. For the sub-fossil *Torneträsk TRW* chronology there is only a small difference in the slopes of the simple RCS and the SF RCS curves (Fig. 1b). The difference between the simple RCS chronology and SF RCS chronology is consequently also very small (Fig. 1d). The sub-fossil trees in this chronology have effectively removed the common-signal bias in the RCS curve demonstrating that in situations where numerous sub-fossil data are available the signal-free method offers little advantage over the non-signal-free approach.

However, for the *Torneträsk Living* chronology the simple RCS curve (Fig. 1a) has a shallower slope over ring ages from 50 to 200 years when compared with the SF RCS curve. This slope difference is caused by what is known to be a temperature related increase in tree growth at around 1920. The effect of this is distributed over the older ring ages of the RCS curve. This difference results in an “end effect” bias in the simple RCS chronology relative to the SF RCS chronology (Fig. 1c). The presence of the 20th century growth-increase signal in the simple RCS curve reduces the amplitude of this growth increase in the simple RCS chronology (Fig. 1c blue). However, the use of the signal-free method removes the common-signal bias from the RCS curve fulfilling the role of the sub-fossil trees and produces a substantially unbiased chronology without the use of sub-fossil trees.

Step change with sub-fossil trees

The *Yamal TRW* data set was adjusted by introducing different step growth changes to all ring measurements from 1880 onwards: firstly, the measurements were increased by 40% and secondly, they were decreased by 40%. Each of the three data sets (step-increase, original and step-decrease measurements) was separately processed using one-curve RCS, without using signal-free and using signal-free. Fig. 2a shows the mean ring width by ring age (un-smoothed RCS curve) for the original values (black), step-increase values (red), and step-decrease values (blue) using simple RCS. Fig. 2b shows un-smoothed SF RCS curves for the same data. The ratio of unsmoothed RCS series generated from step-increase (red) and step-decrease (blue) measurements to the unadjusted

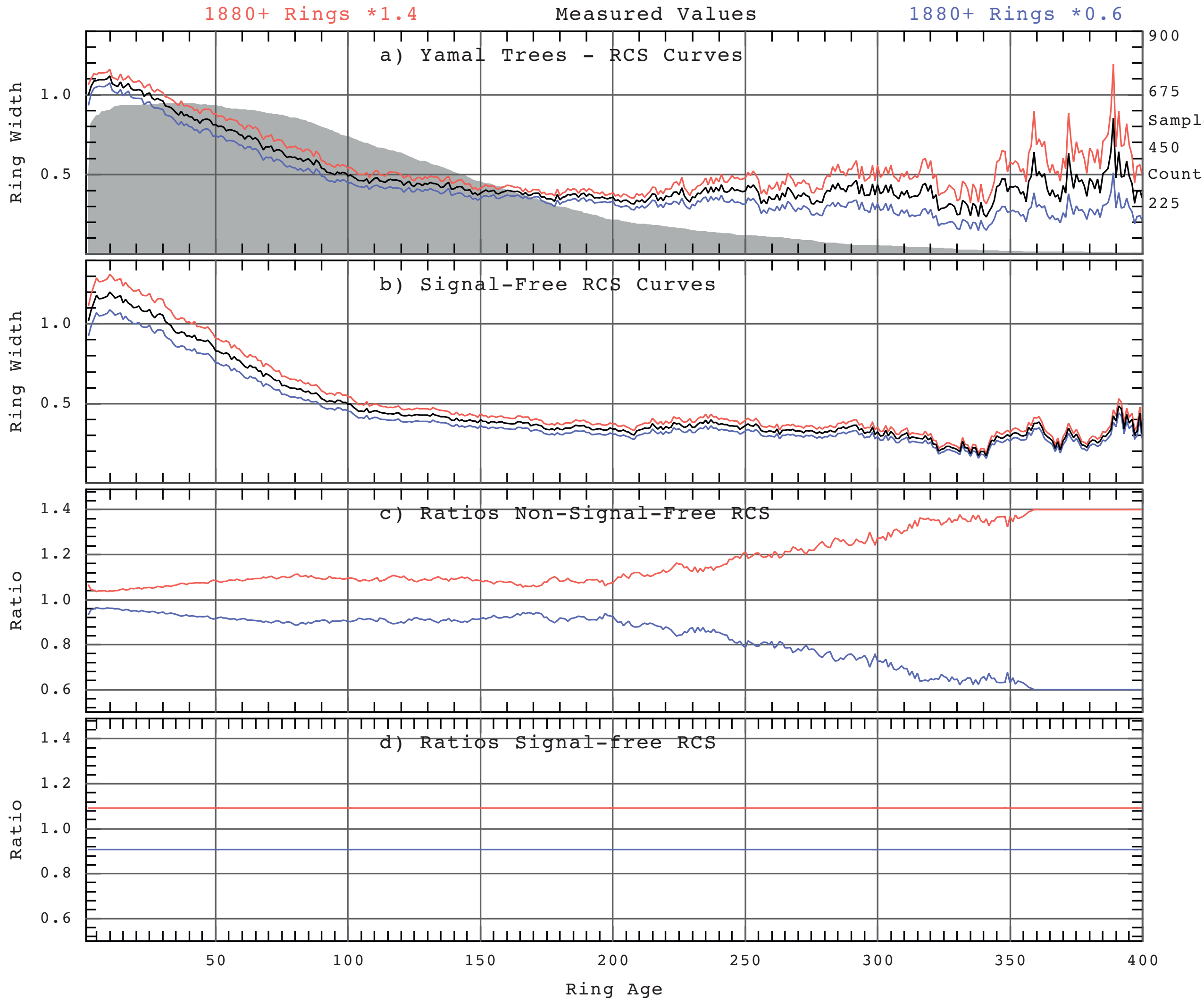

Fig. 2. Unsmoothed RCS curves associated with chronologies in Figure 3. The *Yamal TRW* measurements (black) were used to generate alternative data sets: one with measured values after 1880 increased by 40% (red) and one with measured values after 1880 reduced by 40% (blue). Sample counts are shown in (a) by grey shading. For each data set, unsmoothed RCS curves for simple one-curve RCS are shown in (a) and alternatively, using the signal-free method in (b). To highlight the differences between the RCS curves, the ratios of the 40% increase RCS curve divided by the original RCS curve (red) and the 40% decrease RCS curve divided by the original RCS curve (blue) for the non-signal-free chronologies are shown in (c) and for the SF RCS chronologies in (d).

data are also shown for simple RCS in Fig. 2c and for SF RCS in Fig. 2d. In Fig. 2a and b, the step-increase and step-decrease RCS curves lie above and below those of the measured values respectively reflecting the overall change to the mean value of TRW generated by the adjustments to the original data. Because the living-tree samples contain a larger proportion of older trees than the sub-fossil samples this is reflected in the RCS curve. For rings > 250 years, the proportion from the 20th century is larger than the proportion from sub-fossil trees (relative to younger ring ages) and there is residual bias from the step changes in the oldest portion of the RCS curve. Because of this residual bias the differences in simple RCS curves are larger (as are the ratios of simple RCS curves) for rings >250-year old than for younger rings. Because the number of rings involved is small the resultant bias in chronologies is small. The common signal has been removed from the SF RCS curves. The signal-free differences simply reflect the imposed change of mean (Fig. 2b) distributed over the full time period as fractional deviations. The ratios of the signal-free step-increase and the signal-free step-decrease RCS curves to the original (measured values) RCS curve are horizontal lines (Fig. 2d). They show no bias and the magnitudes of the differences correctly reflect the artificial changes made to the mean values of the TRW data.

Fig. 3a shows 50-year smoothed chronologies made from the calendar-year means of the original (black), step-increase (red) and step-decrease (blue) data allowing comparison of the effect of the introduced step changes at 1880. The count-weighted mean values of all chronologies will be 1.0 and the increase (or decrease) after 1880 will produce a corresponding decrease (increase) in index values before 1880 in the chronologies created from adjusted measurements relative to those created using the original measured values. The smoothed chronologies generated from original, step-increase, and step-decrease values using simple RCS (Fig. 3b) and SF RCS (Fig. 3c) appear to have captured the artificial change to the measurements with little distortion. The ratios of step-increase and step-decrease chronologies against the original chronology for the simple RCS (Fig. 3d) appear noisy but with little distortion to the low-frequency variance of the artificial change. This shows that this chronology containing sub-fossil samples, despite some distortion in the older parts of the RCS curves, has successfully captured the artificial change. The ratios of

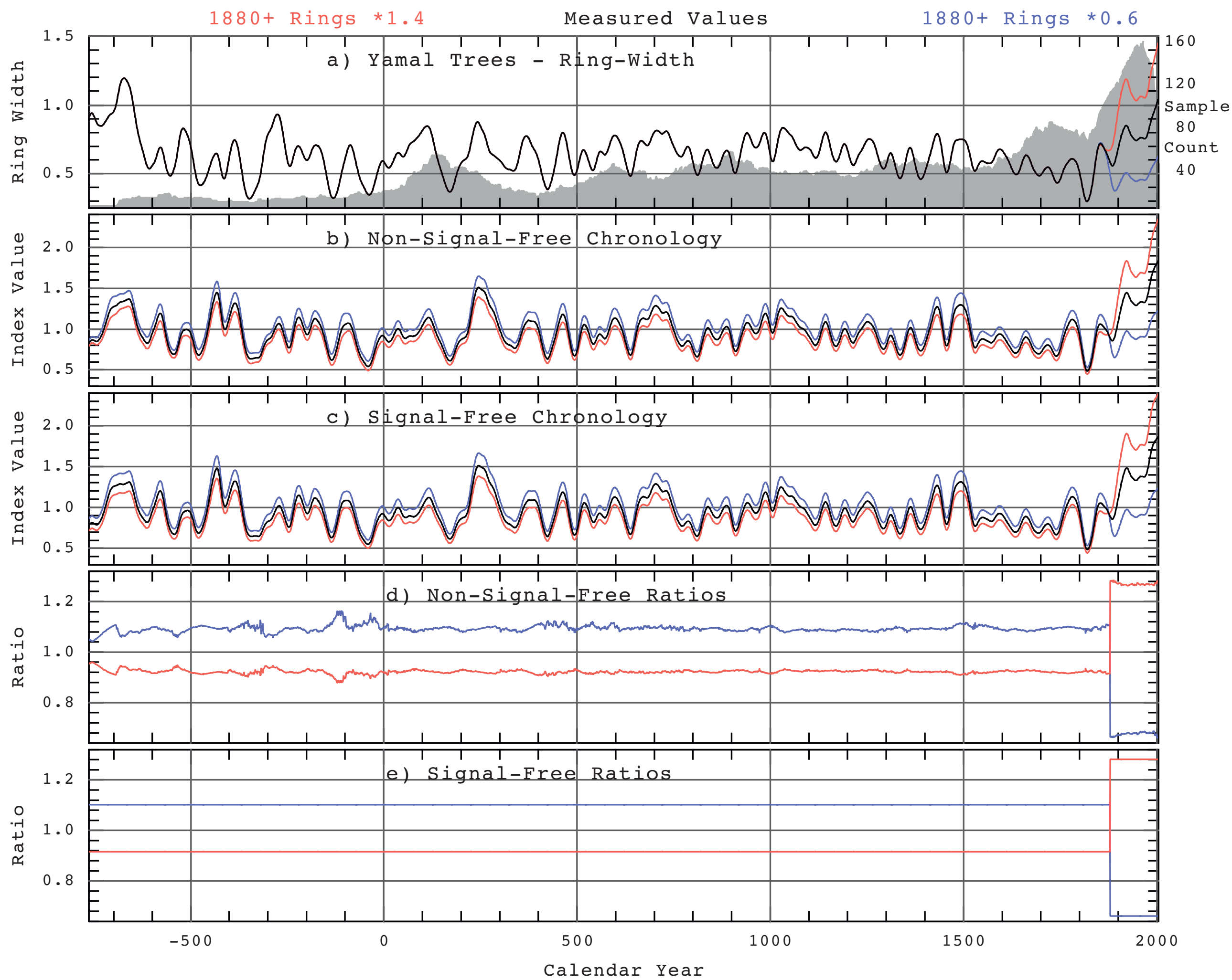

Fig. 3. The *Yamal TRW* measurements (black) were used to generate alternative data sets: one with measured values after 1880 increased by 40% (red) and one with measured values after 1880 reduced by 40% (blue). Sample counts and the means of the three (original, 40% increase and 40% decrease) measurement series are shown by calendar year in (a). Chronologies were generated from the three data sets using simple one-curve RCS without the signal-free method (b) and alternatively using the signal-free method (c). Differences in the generated chronologies are shown by the ratios of the 40% increase chronology divided by the original chronology (red) and the 40% decrease chronology divided by the original chronology (blue) for the non-signal-free (d) and signal-free (e) chronologies.

step-increase and step-decrease chronologies against the original chronology for the SF RCS (Fig. 3e) show that the artificial change has been exactly retained without any distortion.

Step change without sub-fossil trees

The *Finnish TRW* data, derived from living-tree samples, were adjusted in two ways by making artificial step growth changes to all rings from 1920 onwards: firstly, a 30% decrease in ring values was imposed and secondly, a 60% decrease in ring values. The selection of these values is discussed in the legend to Figure SM01. Because the chronology contains a natural growth increase at circa 1920, the 30% decrease values represent a data set with "zero step" (i.e. no change after 1920) against which data sets with a step increase after 1920 (i.e. the existing unadjusted measurement data) and a step decrease after 1920 (the 60% decrease data) are compared. The three data sets were separately processed using one-curve RCS without using signal-free and using the signal-free method. The unsmoothed RCS curves for the step-increase values (red), the zero-step values (black) and the step-down values (blue) of simple and SF RCS are shown in Fig. 4. Because the artificial changes are imposed over the period after 1920 while the majority of rings grew before this date, the earliest values (younger rings) of the simple RCS curves (Fig. 4a) are little changed while the differences between curves become progressively larger as ring age increases. The ratios of step-increase and step-decrease RCS curves (Fig. 4c) to the zero-step RCS curve shows a markedly increasing difference between curves as ring age increases. The difference between RCS curves is slightly less at around ring age 300, the result of the cohort of 250–300 year old trees dropping out of the RCS curves. The presence of the common signal (artificial change) has clearly distorted the shape of the RCS curves created using simple RCS. The common signal has been removed from the SF RCS curves so that they appear to be unaffected by the artificial step changes in the common signal after 1920. The SF RCS curves simply reflect the change of mean (Fig. 4b) distributed over the full time period as fractional deviations. The ratios of the signal-free step-increase and step-decrease RCS curves to the zero-step RCS curves are horizontal lines (Fig. 4d) correctly showing the expected step change at 1920.

Fig. 5a shows the chronologies of mean TRW for the original measured values (red), the 60% step decrease (blue), and the 30% step decrease (black) data, referred to as step-increase, zero-step and step-decrease chronologies. The count-weighted mean value of an RCS chronology will be approximately 1.0. The step-increase

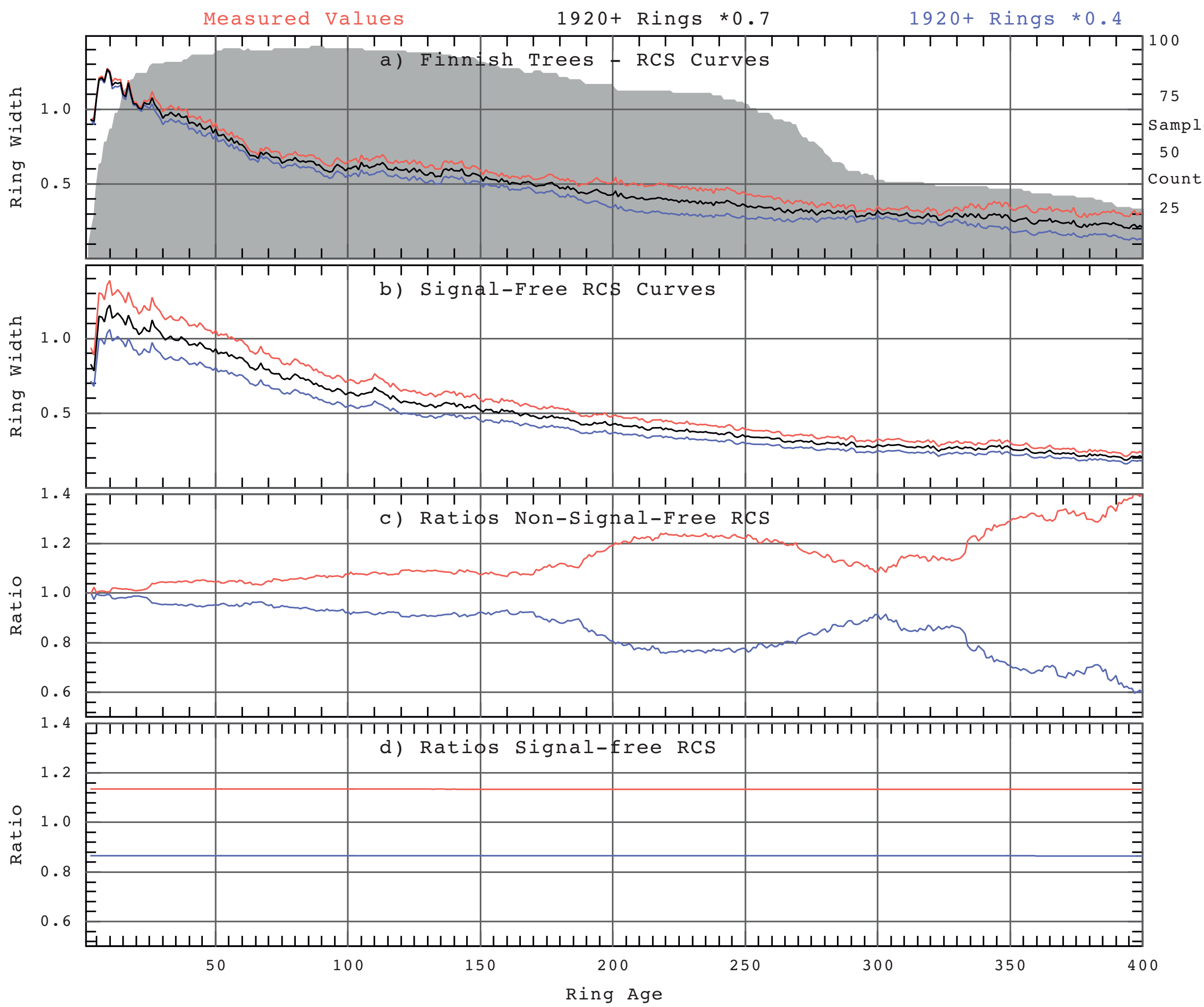

Fig. 4. Unsmoothed RCS curves associated with chronologies from Fig. 5 created from *Finnish TRW* data. Sample counts (grey shading) are shown in (a). The means of TRW by ring age for the measured values (red), 30% decrease after 1920 chronology (black), and 60% decrease after 1920 chronology (blue) referred to as step-increase, zero-step and step-decrease data are shown in (a) and (b). Unsmoothed RCS curves for one-curve RCS without using the signal-free method are shown in (a) and alternatively using the signal-free method (b). To highlight the differences in the generated RCS curves, the ratios of firstly the step-increase RCS curve divided by the zero-step RCS curve is shown in (red) and secondly the step-decrease RCS curve divided by the zero-step RCS curve is shown in (blue) for the non-signal free (c) and signal-free method (d).

(step-decrease) chronology will have lower (higher) values before 1920 relative to the zero-step chronology. For simple RCS prior to 1920 (Fig. 5b), the slope of the step-increase chronology is less than the slope of the zero-step chronology and the slope of the step-decrease chronology is greater than the slope of the zero-step chronology. The ratios of chronologies (Fig. 5d) of step-increase and step-decrease divided by the zero-step chronology show that the effect of the artificial step changes is to produce a consistent slope bias in these non-signal-free chronologies over their full period. Using simple RCS the overall slope of a chronology without sub-fossil trees is unpredictable. What has occurred is that the change to the common signal at 1920 (step-increase or step-decrease) is distributed across the older section of the RCS curve because the constituent tree ages vary considerably. This has changed the slope of the RCS curve and this change of slope produces the slope bias in the chronologies. The proportion of chronology slope generated from the changing mean values of tree index-series (caused by changing common forcing over time) is captured by simple RCS. The proportion of chronology slope generated from the average slope of series of tree indices (the average slope of common forcing over the life of a tree) has been lost. The chronologies generated using SF RCS (Fig. 5c) have captured the artificial change to the measurements with little distortion as is shown by the ratios of both step-increase and step-decrease chronologies against the zero-step chronology for the SF RCS implementation (Fig. 5e).

Chronology slope recovery using simulated trees

It is known that for RCS the existence of a tree-growth-forcing trend over the length of the chronology can cause problems (Briffa and Melvin, 2011). In this case, measurements from the "average" tree will contain the average chronology slope over the tree's lifetime. An RCS curve constructed from such trees will contain this slope and the division by RCS values when detrending each series will remove the slope (Briffa and Melvin, 2011, Figure 5.2). The effects of positive and negative growth-forcing slopes on RCS curves and resulting chronologies are explored here using simulated trees. Pseudo sub-fossil and living-tree chronologies were generated from series of simulated TRW measurements. The simulated chronology signals consisted of either a positive or negative linear slope over the length of the chronology with a range

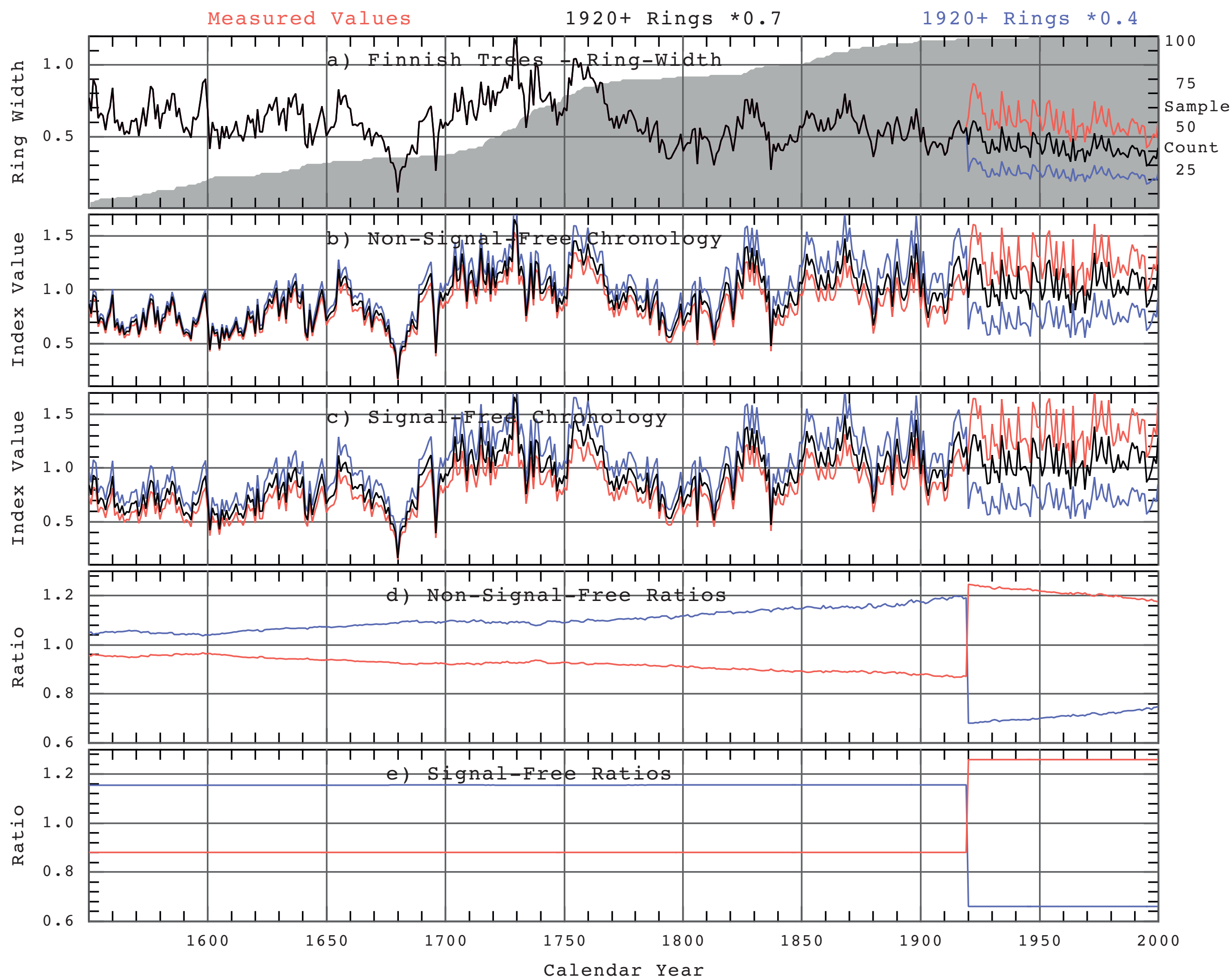

Fig. 5. The *Finnish TRW* measurements (red) were used to generate alternative data sets: one with measured values after 1920 reduced by 30% (black) and one with measured values after 1920 reduced by 60% (blue). Sample counts and the mean of the three (original here containing a natural "step-increase", 30% decrease "zero-step", and 60% decrease "step-decrease") measurement series are shown by calendar year in (a). Chronologies were generated from the three data sets with one-curve RCS without using the signal-free method (b) and alternatively using the signal-free method (c). Differences in the generated chronologies are shown by the ratios: firstly, of the step-increase chronology divided by the zero-step chronology (red) and secondly, the step-decrease chronology divided by the zero-step chronology (blue) for the non-signal-free chronologies (d) and for the SF RCS chronologies (e).

from 0.8 to 1.2. TRW measurements consist of the chronology values over the life of the tree multiplied by "white noise" with a range 0.95–1.05. All pseudo trees have start dates evenly-spaced over time. The pseudo-sub-fossil trees are all 200 years old and the living trees all have the same final year. The four data sets were standardised using simple one-curve RCS and one-curve SF RCS. The chronologies are shown in Fig. 7 and the associated RCS curves are shown in Fig. 6. The simple RCS chronologies derived from simulated sub-fossil trees, (Fig. 7a and b, blue lines), show an end-effect distortion. The average slope of the chronology over the life of each tree appears in the RCS curve (Fig. 6a and b) and is removed from each individual tree-series in detrending. In the central portions of the chronologies (between nominal years 200 and 800) the chronology slope is correctly captured by the changing mean values of tree-index series. The loss of slope of trees (decrease at the start and increase at the end of each series of tree indices) in this section of the chronology does not change the chronology because the beginning of one tree overlaps with the end of another tree and these effects cancel. At the start (and end) of the chronologies there are no second-halves (first halves) of trees to compensate and the loss of slope produces systematic bias in the beginnings and ends of these chronologies. The simple RCS living-tree chronologies (Fig. 7c and d, blue curves) lose the slopes contained in the respective RCS curves (Fig. 6c and d) but in each case they do retain the slope related to the changing mean values of each tree-index series. In this example the early and late end-effect biases effectively join in the middle of the chronology so that the living-tree chronology processed without using the signal-free implementation suffers a serious partial loss of chronology slope. In the corresponding examples, where there is a wide distribution of tree ages, the signal-free method overcomes this slope bias problem (Fig. 7c and d, red curves).

Chronology slope change using living trees

The *Finnish TRW* measurements were adjusted to generate alternative data sets: one with the chronology slope reduced (decreased slope) and one with the chronology slope increased (increased slope), where each measurement was multiplied by the appropriate factor for that year to rotate the chronology about the centre year of the chronology, with a change of slope of 0.001 mm per year. The unsmoothed RCS curves for the original, increased-slope and decreased-slope data with and without using the signal-free

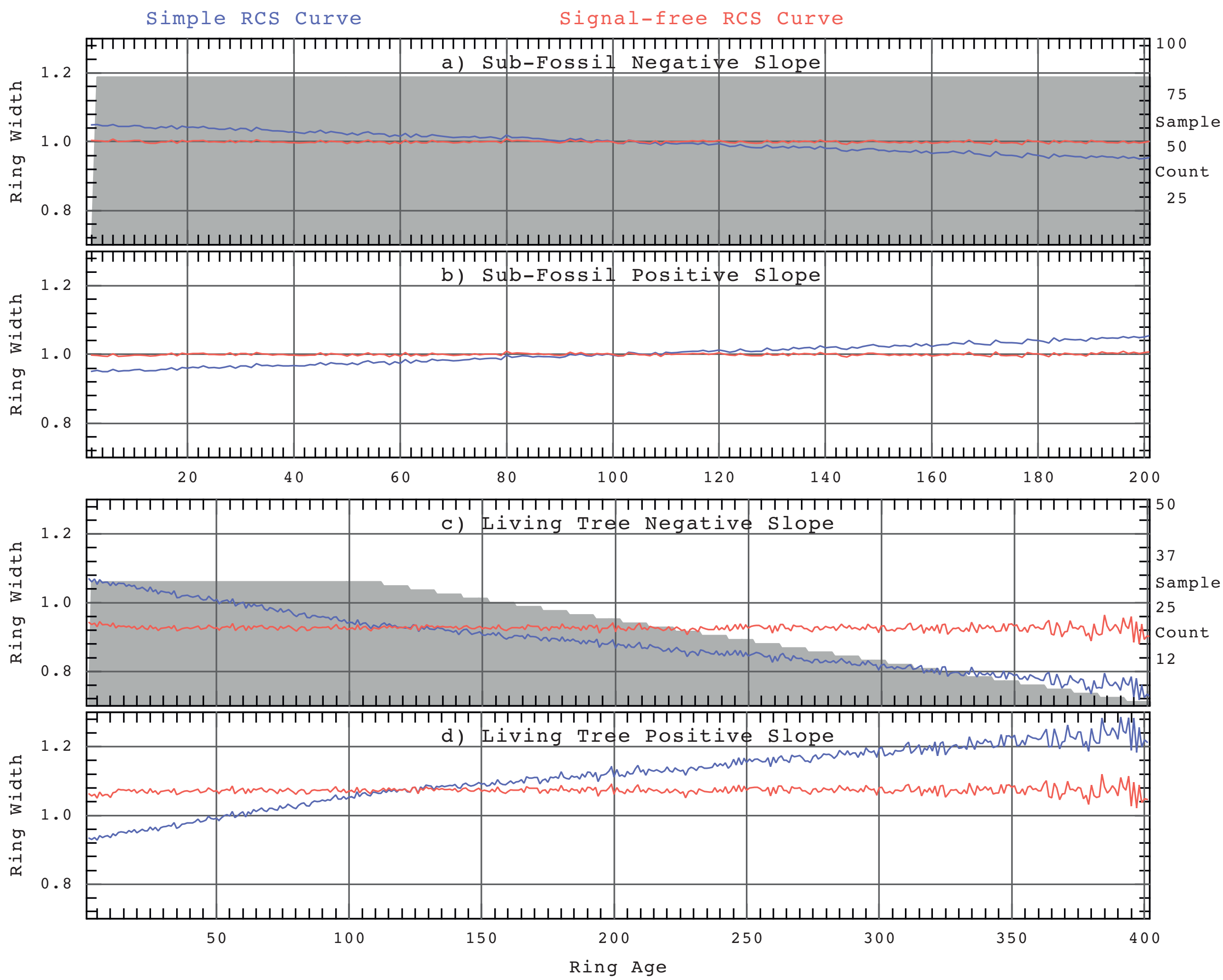

Fig. 6. Unsmoothed RCS curves associated with chronologies in Fig. 7. Sub-fossil and living chronologies were generated from series of simulated TRW measurements. The simulated chronology signals consisted of either a positive or negative linear slope over the length of the chronology. TRW measurements consist of the chronology values over the life of the tree with added random "noise". The four data sets were standardised using simple one-curve RCS (blue) and one-curve SF RCS (red). In (a) and (b) the slope of the chronology over 1000 years appears identically in each 200-year long tree. This slope appears in the simple RCS curves but does not appear in the SF RCS curves. In (c) and (d) the slope of the chronology over 400 years appears in each tree. Because the mean values of the younger trees are greater for the negative (c) slope (and lower (d) for the positive slope) than those of the oldest trees the RCS curves of the simple RCS (blue) are not straight lines but curve slightly. The signal-free method successfully removes the influence of the artificial signals added to these trees on the shape of the RCS curves in all cases. Sample counts are shown by grey shading.

method are compared (see Figure SM02 and associated discussion). The simple RCS curves contain the slope changes whereas the SF RCS curves are unbiased by the slope change. Chronologies for the original, increased-slope and decreased-slope data with and without using the signal-free method are shown in Fig. 8. The simple RCS chronology recovers the slope contained by the means of series of tree indices but loses the portion of slope contained in the slopes of series of tree indices (Fig. 8d). The signal-free method recovers both types of slope and thus successfully recovers the artificial changes made to the original data (Fig. 8e).

The slope of a living-tree RCS chronology comes from both the changing mean values of series of tree indices over time and the mean of the slopes of series of tree indices. To evaluate their separate contributions we explored the effects on living-tree chronologies of changing the means of series of tree indices without changing the slopes and changing the slopes of series of tree indices without changing the means. For this we used artificially adjusted versions of the *Finnish TRW* data. Firstly, slope changes were applied to individual series of measurements but the mean of each series was left unchanged (Figures SM03 and SM04 and associated discussion). This demonstrates that the mean values of index series over time is an important contributor to chronology slope in a living-tree chronology and is necessary for the successful operation of SF RCS. Secondly, the effect of changing the chronology slope was applied to the mean TRW of individual measurement series but the slopes of each series were left unchanged (Figures SM05 and SM06). This indicates that the slopes of measurement series over time also make an important contribution to chronology slope in living-tree chronologies and are also necessary for the successful operation of SF RCS. To recover the full chronology slope, the signal-free method requires that the two components of the slope i.e. that contained in the mean values of index series and that contained in the slopes of those series, are present in the measurement series.

Living trees with reduced time span

The requirement for large numbers of sub-fossil trees can be relaxed with the use of SF RCS provided rings of the same age are distributed over a wide time range. Incorporating a wider range of tree starting years (i.e. a wide range of ring ages in living-tree

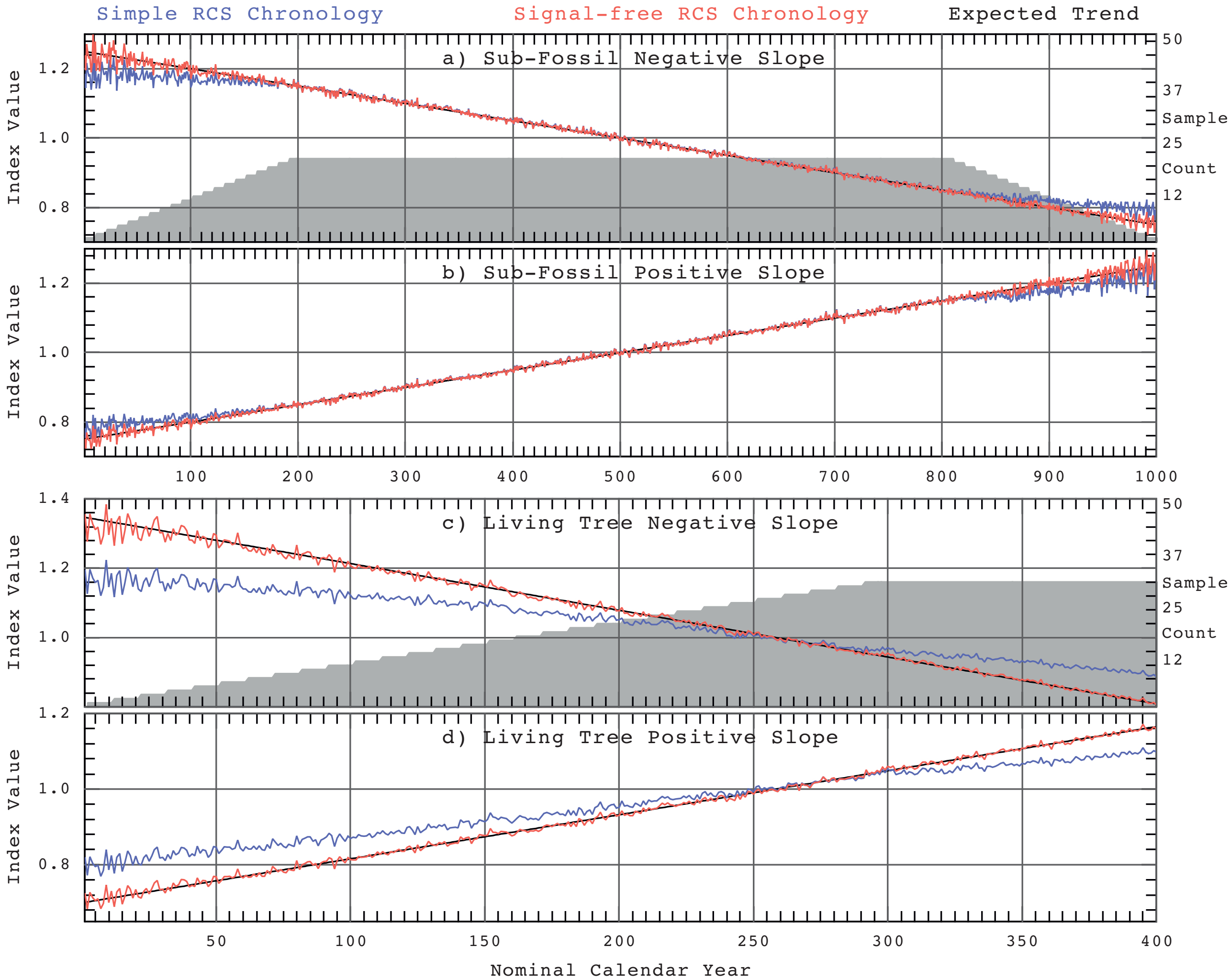

Fig. 7. Sub-fossil and living chronologies were generated from series of simulated TRW measurements consisting of either a positive or negative linear slope over the length of the chronology with added random "white noise". The four data sets were standardised using simple one-curve RCS and one-curve SF RCS. In each case the expected chronology signal is plotted as a black line. The simple RCS chronologies (blue) and SF RCS chronologies (red) derived from simulated sub-fossil trees are shown in (a) and (b) and those generated from simulated living trees are shown in (c) and (d). Sample counts are shown by grey shading.

data) produces a wider range of climate variability experienced at each ring age and reduces the probability that climate from one specific period will unduly influence the shape of the RCS curve. Here we consider how wide the time range must be to avoid distortion in chronologies. The three *Finnish TRW* data sets (step-increase, zero-step and step-decrease) as described in *Step change without sub-fossil trees* are used. The trees in these data sets end on the same year so the variation in start dates represents the spread over time of rings of the same ring-age. By systematically removing trees, different data sets are created in which the range of start dates (and ages) of the remaining trees is reduced and thus each ring age of the RCS curve is represented by rings from a different restricted time range. Five data sets, (a) to (e), were developed with different starting-date (and tree-age) ranges as shown in Table 1.

Detailed results are shown in Figures SM07 to SM11 for non-signal-free and signal-free processing. These results show that without signal free, whatever the range of start dates for trees, the simple RCS performs poorly with these adjusted-living-tree data sets and consistently creates chronologies whose slopes do not reflect the applied changes. Fig. 9 summarises the results for SF RCS. The ratios of step decrease chronology to zero step chronology (blue dashed lines) and the ratios of step increase chronology to zero step chronology (red lines) are plotted using data from (a) 66 trees with a 243-year range in starting years (from 1704 to 1946), (b) 55 trees with a 183-year range (from 1704 to 1882), (c) 40 trees with a 71-year range (from 1704), (d) 53 trees with a 155-year range (from 1620), and (e) 74 trees with a 225-year range (from 1550). For (a) and (e) there is no distortion in the captured signal, while for (b) and (d) there is slight distortion. For (c) there is considerable distortion in the recovered signals. As the starting-year range is reduced below 200 years some distortion appears even when using the signal-free method and with a starting-year range of length less than 100 years distortion is considerable. Figure SM12 shows results similar to Fig. 9 except that the artificial adjustments in this case, instead of step changes are a slope increase and a slope decrease. This demonstrates that the ability to capture slope changes is very similar to that for step changes. With only 71 years variation in ring start dates the signal-free method cannot recover the artificial changes correctly. In this example, simply including either 15 younger or 13 older trees substantially corrects the problem and including either 26 younger or 34 older trees completely corrects the problem. Provided that there is a sufficiently wide distribution of tree ages, the SF RCS can

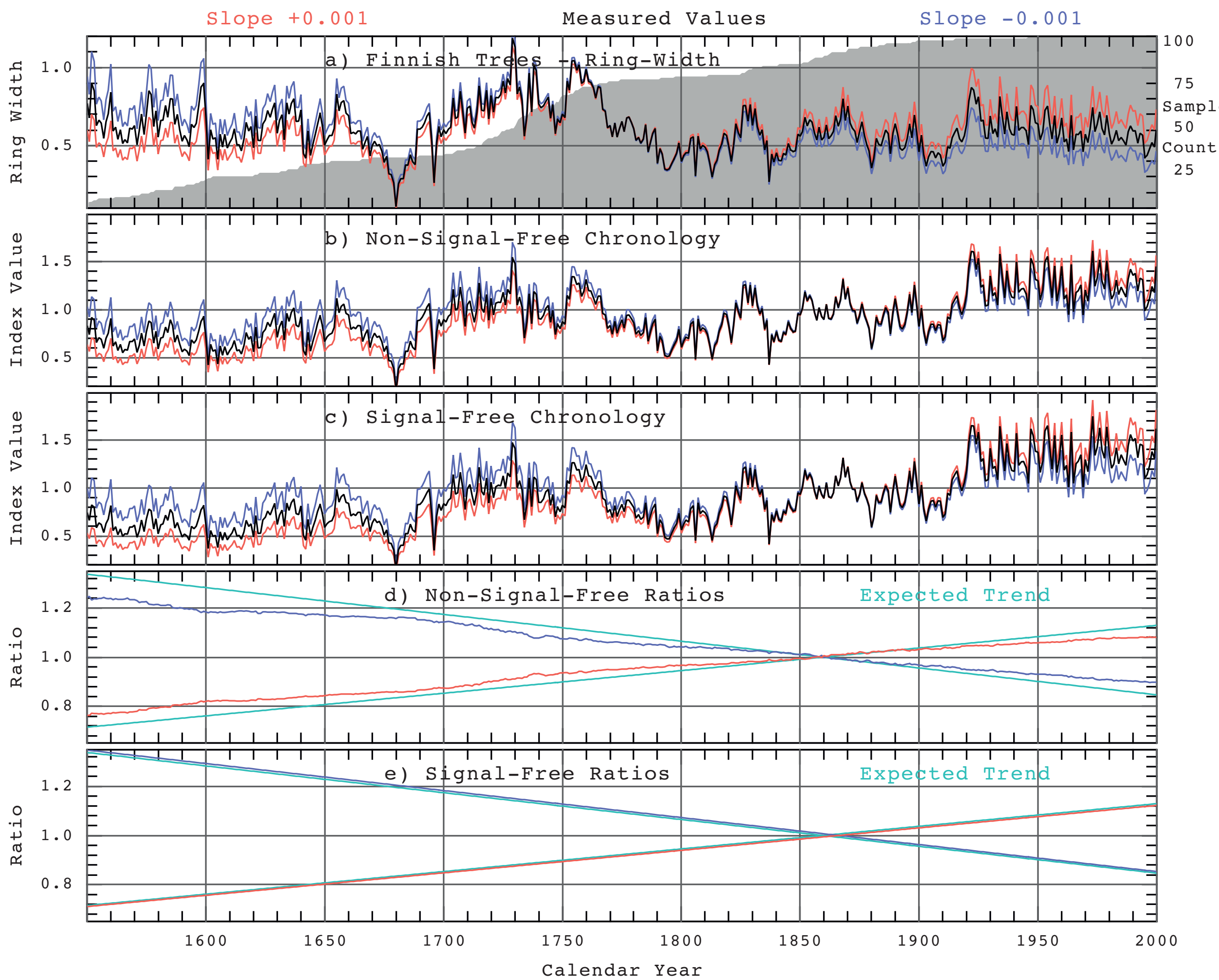

Fig. 8. The *Finnish TRW* measurements (black) were used to generate alternative data sets: one with the chronology slope reduced (blue) and one with the chronology slope increased (red), where each measurement was multiplied by the appropriate factor for that year to rotate the chronology about the centre year. Sample counts and the means of raw measurement series are shown in (a). Chronologies generated from the three data sets standardised with one-curve RCS without using the signal-free method are shown in (b) and alternatively using the signal-free method (c). To highlight the differences in the generated chronologies, the ratios of firstly the increased-slope chronology divided by the original chronology (red) and secondly the decreased-slope chronology divided by the original chronology (blue) are shown for non-signal-free chronologies (d) and the SF RCS chronologies (e). The expected trend ratios are shown as cyan lines in (d) and (e).

accurately recover the slope. The tests applied here (using step or slope increase or decrease changes) are able to identify this problem.

Description of CRUST software

CRUST concept and background

CRUST provides the means of standardising various types of tree-ring data using SF RCS as well as other approaches and a range of specific implementation options that may be selected for whatever approach is used. The program was originally conceived as a tool for interactive experimentation with different standardisation methods. It is assumed that the user is familiar with the background concepts underlying the standardisation of tree-ring measurements and is, therefore, able to make "informed" choices when using this software. For background and general discussion of tree-ring standardisation (see Fritts, 1976, Chapter 6, Cook, 1985; Cook et al., 1990; Melvin, 2004; Briffa and Melvin, 2011).

Table 1
Details of the *Finnish TRW* data with different starting date ranges (used to produce Fig.9 and SM07 to SM12): for each data set the number of trees, first starting year, last starting year, minimum ring age, maximum ring age and the range of years are shown.

Plot	No. of trees	Start year		Tree age		Range
		First	Last	Minimum	Maximum	
a	66	1704	1946	55	297	243
b	55	1704	1886	115	297	183
c	40	1704	1774	227	297	71
d	53	1620	1774	227	381	155
e	74	1550	1774	227	451	225

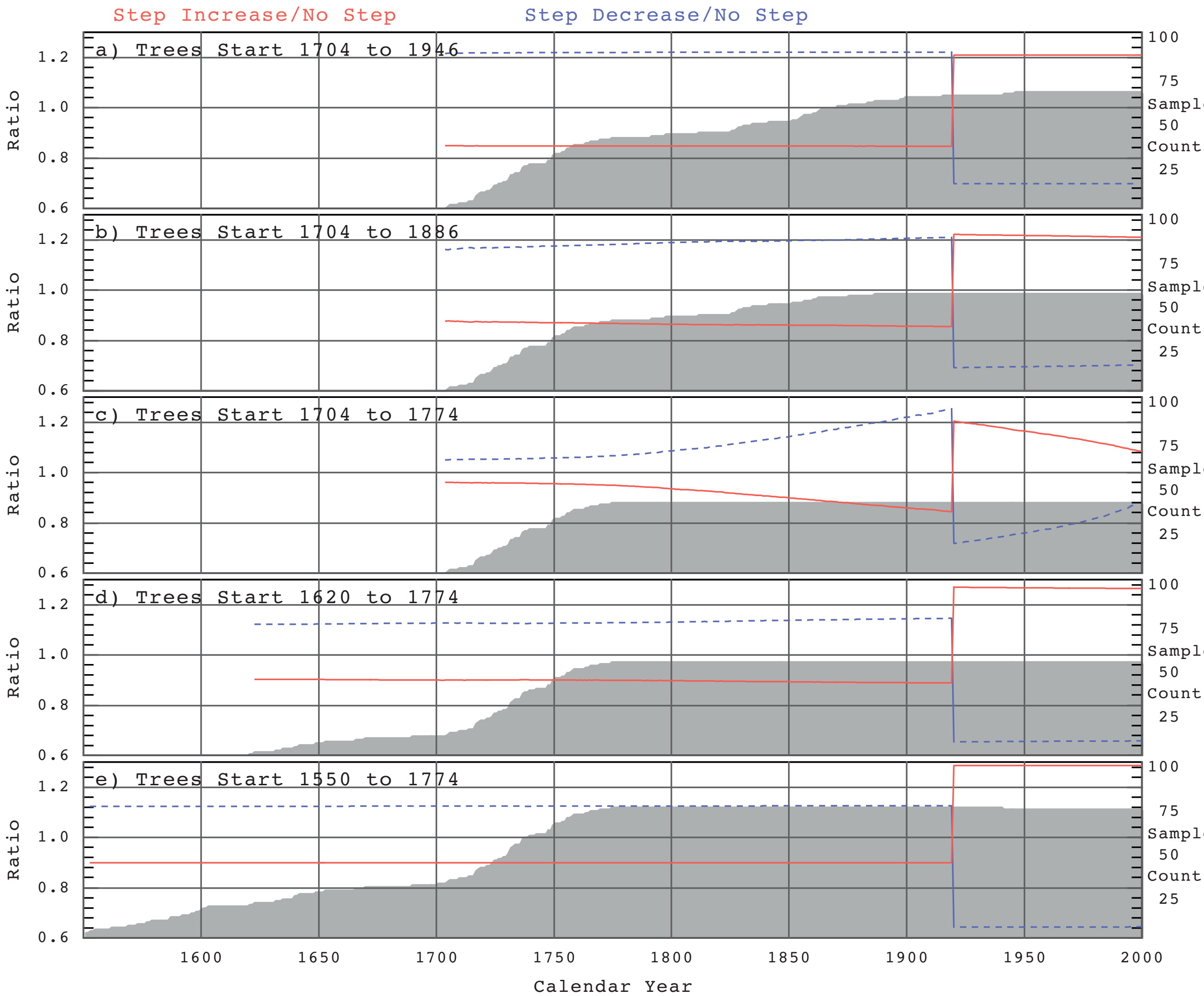

Fig. 9. The *Finnish TRW* measurements (with natural step increase) were used to generate alternative data sets: one with measured values after 1920 reduced by 30% (zero-step) and one with measured values after 1920 reduced by 60% (step decrease). Various subsets of these data, distinguished by the age distribution of trees, were standardised using one-curve, SF RCS. The ratio between the step-increase and the zero-step chronologies (red) and the ratio between the step-decrease and the zero-step chronologies (blue dashed line) are plotted for (a) the 66 series of tree measurements starting between 1704 and 1946, (b) the 55 series starting between 1704 and 1886, (c) the 40 series starting between 1704 and 1774, (d) the 53 series starting between 1620 and 1774, and (e) the 74 series starting between 1550 and 1774.

In CRUST, various input data may be selected, processed in different ways and the results displayed quickly and conveniently on screen. The program is controlled using a mouse to access an interactive graphical menu system. However there is also a batch processing option that allows the user to create a control file specifying input data files and program parameters. When running the program in interactive or batch mode many options create a record and general report of progress which is saved as a report file. Besides offering a convenient basis for experimenting with different standardisation methods a major focus, and the principal originality represented by CRUST, is the ability to perform “Signal-Free” processing with RCS standardisation.

The original concept followed in developing CRUST was that of the ARSTAN Software (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software) developed and maintained by Ed Cook, Tree-Ring Laboratory, Lamont-Doherty Earth Observatory and Paul Krusic, Bert Bolin Centre, Stockholm University. ARSTAN was written principally to perform auto-regressive standardisation: where a mean-value function of residual series is produced from pre-whitening measurements from individual trees and an estimate of the average persistence is then added back to the mean residual series (Cook, 1985). ARSTAN also allows smoothing splines with various degrees of flexibility to be used as standardisation curves (Cook and Peters, 1981) or as a precursor to the use of auto-regressive standardisation.

ARSTAN also incorporates standardisation options employed in much earlier software, INDEXA written at the Laboratory of Tree-Ring Research in Tucson (Fritts, 1963; Fritts et al., 1969). This incorporated detrending of measurement series by taking differences or ratios from negative exponential curves (or negative exponential curves modified by the addition of a constant), as well as options to use sloping or horizontal straight lines fitted through the measurement data. A related and widely used approach to the use of negative exponential standardisation curves is the use of the compound exponential or Hugershoff curve (Bräker, 1981). All of these early options and a basic facility to use the autoregressive standardisation approach are incorporated within CRUST. Much of the code used in CRUST was converted from that of ARSTAN and this is gratefully acknowledged here.

A very basic outline of the major processing options available within CRUST is provided below. This is included here only to illustrate the scope of the software. More details are to be found in the "CRUST: Program Documentation" available at http://www.cru.uea.ac.uk/cru/papers/melvin2013dendrochronologia/. There is also some online help provided when CRUST is used in interactive mode, through a number of drop-down dialogue boxes accessed using the right button of the mouse.

Principal CRUST standardisation options

The following is a list of the major options available for selection within CRUST. The expressions in parentheses identify the specific control parameters used within CRUST. A number of these options are from those available within other standardisation software.

Detrending Method (IDT) select from: RCS method; no detrend; modified negative exponential or any slope line; modified negative exponential or a negative slope line; any slope line; negative slope line; horizontal line; Hugershoff curve; general exponential; and various smoothing splines.

Transform options (ITN) select from: no transform; adaptive power transform; or basal area transform.

RCS curve smoothing (RDT) select from: age dependant spline; unsmoothed RCS curve; modified negative exponential; fitted straight line; Hugershoff curve; spline with selected stiffness; or spline with % length stiffness.

Index Creation options (IND) select from: ratios or residuals to create tree index series.

Index Averaging options (KRB) select from: arithmetic mean or robust mean.

Variance Stabilisation options (ISB) select from: no variance stabilisation; variance stabilisation; or high-frequency-only variance stabilisation.

Signal-Free (SFO) select from: signal-free or not signal-free.

Pith-Offset Estimates (POO) select from; use pith offset estimates or do not use pith offset estimates.

Single RCS Curve (SRC) select from: single RCS curve; multiple-RCS curves; or the use of pre-specified RCS curves.

Type of RCS curve (TRC) select from: use age-based RCS curves; use diameter-based RCS curves; or use the average of age- and diameter-based RCS curves.

RCS Transform options (GTR) select from: use un-transformed indices or indices transformed by mean growth rate.

Tree Sorting options (TST) select from: do not sort; sort by tree age; sort by tree diameter; sort by growth rate; sort by tree name; sort by pith year; or sort by final year.

Chronology Mean options (BFC) select from: mean of all tree indices; or arithmetic mean of chronologies; or the mean with chronology means set to 1.0.

Normal Distribution option (BFC) select from: use untransformed indices; or convert tree index distribution to normal.

Autoregressive Modelling options (BFC) select from: create the STD chronology; create the ARS chronology; or create the RES chronology.

Conclusions

We have reviewed the basic concepts of simple and signal-free RCS and described the implementation options available within CRUST. We have demonstrated superior performance of the signal-free approach in a number of examples selected to test the ability of RCS to recover known growth-forcing signals. The overall slope of living-tree chronologies generated using simple RCS is uncertain because the chronology slope appears in the RCS curve and is largely removed from the chronology by division. This problem severely limits the value of the simple RCS method for processing living-tree chronologies. As previously described, the availability of large numbers of sub-fossil trees spanning a period much longer than the length of individual trees will, in general, greatly reduce this problem so that it becomes only an "end effect" bias often of relatively small magnitude. The signal-free method reduces the requirement for a large temporal distribution of trees (i.e. many sub-fossil trees) and mitigates the "end-effect" bias. RCS is unsuitable for processing the data from a near equal-aged cohort of trees whose growth terminates at the same time. A sample living-tree chronology processed using the signal-free method showed no distortion in the recovery of imposed signal changes where the range of tree ages spanned at least half the length of the chronology. Distortion was significant when the age range was less than one quarter the length of the chronology.

By artificially adjusting chronologies it is possible to test the likely presence of bias in the slope of those chronologies. If applied changes representing known growth-forcing signals can be recovered without serious distortion it is reasonable to assume that the signal recovered from the original chronology is also undistorted. However, if the known signals are distorted then it may be that the original chronology is distorted. Only a limited extent of experimentation with the SF approach has been done to date and there is considerable scope for further work in other contexts. However, on the basis of results to date we conclude that Signal-Free RCS should be used as the standard method of RCS processing.

The signal-free approach clearly improves the performance and extends the situations in which RCS can be used. However, it is important to stress that its value lies in its ability to mitigate only one source of potential bias: the distortion in RCS curves associated with residual common-signal variance. As with simple RCS the SF RCS cannot overcome chronology bias caused by inhomogeneous samples, particularly the "modern sample bias" associated with the unintentional selection of recent, relatively fast-growing tree samples that are inconsistent compared with sample composition back in time (Briffa and Melvin, 2011).

In Part 2 of this paper we discuss the justification and make recommendations for the use of other CRUST implementation options. These include: the use of pith offset data; using ratios rather than differences in calculating chronology indices; the transformation of tree indices so that they have a normal distribution; an alternative calculation of EPS with a focus on low-frequency chronology confidence and the use of multiple rather than single RCS curves to overcome modern sample bias.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dendro.2013.06.002.

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